

Research papers

Beyond 'flood hotspots': Modelling emergency service accessibility during flooding in York, UK

Daniel Coles^a, Dapeng Yu^{b,*}, Robert L. Wilby^b, Daniel Green^b, Zara Herring^c^a Leicester City Council, 91 Granby Street, Leicester, UK^b Centre for Hydrological and Ecosystem Science, Department of Geography, Loughborough University, Loughborough, UK^c RPS Environmental Management Ltd, UK

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ABSTRACT

This paper describes the development of a method that couples flood modelling with network analysis to evaluate the accessibility of city districts by emergency responders during flood events. We integrate numerical modelling of flood inundation with geographical analysis of service areas for the Ambulance Service and the Fire & Rescue Service. The method was demonstrated for two flood events in the City of York, UK to assess the vulnerability of care homes and sheltered accommodation. We determine the feasibility of emergency services gaining access within the statutory 8- and 10-min targets for high-priority, life-threatening incidents 75% of the time, during flood episodes. A hydrodynamic flood inundation model (FloodMap) simulates the 2014 pluvial and 2015 fluvial flood events. Predicted floods (with depth >25 cm and areas >100 m²) were overlain on the road network to identify sites with potentially restricted access. Accessibility of the city to emergency responders during flooding was quantified and mapped using; (i) spatial coverage from individual emergency nodes within the legislated timeframes, and; (ii) response times from individual emergency service nodes to vulnerable care homes and sheltered accommodation under flood and non-flood conditions. Results show that, during the 2015 fluvial flood, the area covered by two of the three Fire & Rescue Service stations reduced by 14% and 39% respectively, while the remaining station needed to increase its coverage by 39%. This amounts to an overall reduction of 6% and 20% for modelled and observed floods respectively. During the 2014 surface water flood, 7 out of 22 care homes (32%) and 15 out of 43 sheltered accommodation nodes (35%) had modelled response times above the 8-min threshold from any Ambulance station. Overall, modelled surface water flooding has a larger spatial footprint than fluvial flood events. Hence, accessibility of emergency services may be impacted differently depending on flood mechanism. Moreover, we expect emergency services to face greater challenges under a changing climate with a growing, more vulnerable population. The methodology developed in this study could be applied to other cities, as well as for scenario-based evaluation of emergency preparedness to support strategic decision making, and in real-time forecasting to guide operational decisions where heavy rainfall lead-time and spatial resolution are sufficient.

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1. Introduction

1.1. An integrated approach to flood emergency response management

The 'Making Space for Water' (DEFRA, 2004) strategy document marked a shift to a more integrated approach to flood management in England and Wales (Hall et al., 2003). The report also highlighted the need to manage all types of flooding, including sewer, surface water and groundwater flooding alongside traditional coastal and

riverine flooding (Johnson and Priest, 2008). Ambulance and Fire & Rescue Services need to be able to respond to and operate during flood events. Accordingly, the UK Civil Contingencies Act 2004 established the framework for civil protection, including the Local Resilience Forum (LRF), the main group focusing on multi-agency emergency response (DEFRA, 2013). LRFs are made up of Category 1 organisations, (such as Local Authorities, the Environment Agency, emergency services and National Health Service trusts), and Category 2 organisations (including utility and transport companies). Recurrent flood episodes in the UK reiterate the need for cooperation between these organisations in the way that they share, coordinate and execute their management responsibilities

* Corresponding author at: Centre for Hydrological and Ecosystem Science, Department of Geography, Loughborough University, Loughborough, UK.

E-mail address: d.yu2@lboro.ac.uk (D. Yu).

– all key factors in determining the success of emergency response (Brown and Damery, 2002).

Emergency services play a crucial role during the flood response process, as they participate in joint command-control structures and are central to rescue and relief efforts (Frost, 2002). Because of the risks posed by flooding, these organisations are encouraged to collectively produce a Multi-Agency Flood Plan (DEFRA, 2014), which can be a valuable tool for flood planners and responders. Jha et al. (2012) highlight the importance of creating an emergency flood plan for coordinating response to a flood event. However, road closures, electrical substation failures, and/or telephone exchanges being cut-off can cause problems. Therefore, contingency plans need to be formulated for these eventualities in order to keep vital services operating, such as identifying alternative sources of electricity for key facilities (such as hospitals) (Jha et al., 2012). The *National Flood Resilience Review* (HMG, 2016) exposes the extent to which significant numbers of critical assets are still vulnerable to flooding in England and Wales. In particular, it highlights that the loss of infrastructure services can have significant impacts on people's health and wellbeing.

Lumbroso et al. (2011) found that flood emergency plans may define the roles and responsibilities of different organisations, but lack detailed information on evacuations, and impacts of floods on critical infrastructure, including the road network. A review of the flood emergency plan used in Cumbria during the 2009 flooding found that emergency responders particularly value tools that help them evaluate the vulnerability of critical infrastructure (such as roads, electricity substations and care homes) during the response phase of a flood emergency (Lumbroso and Vinet, 2012). Furthermore, McCarthy et al. (2007) found that models of breach locations and inundation extent were considered useful by emergency responders in the Thamesmead area of London when planning for evacuations or deciding where to allocate resources. Although tools used to determine the extent of flooding (e.g. flood hazard maps) are often well integrated into flood emergency plans in the UK (98% of flood managers said that they used fluvial flood hazard maps to inform emergency plans), other instruments, such as those for assessing the accessibility of inundated roads and evacuation routes, are seldom used (Lumbroso and Vinet, 2012).

Flood emergency plans also need to consider the needs of vulnerable groups, such as the elderly or disabled, as they may need special assistance during flood events (Sene, 2008). Large proportions of the elderly population live in either care homes (where continuous support is provided) or sheltered accommodation (which allows residents more independence while still having the security of a warden) (Shelter England, 2016). However, members of the public have argued that local authorities are good at identifying vulnerable groups when they are located together in care homes or hospitals, but are less able to locate vulnerable individuals in the community (Houston et al., 2011).

1.2. Legislated response times

Emergency responders are often legislated to meet defined response times. For example, UK legislation requires that emergency responders comply with strict timeframes when reacting to incidents. Category 1 responders such as the Ambulance Service and the Fire & Rescue Service are required to reach 75% of 'Red 1' (high-priority, life-threatening incidents) in less than 8 and 10 min respectively from the time when the initial call was received. This includes blue-light incidents such as life-threatening and traumatic injury, cardiac arrest, road collisions, and individuals trapped by floodwaters. In 2015, the BBC reported that the East Midlands Ambulance Service (EMAS) had failed to meet targets to reach the highest priority calls in 8 min for a fifth

year running. Rising demand combined with inefficient call handling and dispatch system are often cited as the reasons for missing this target. However, response times can also be affected by flood episodes which may limit the ability of emergency responders to navigate through a disrupted road network. The impact of flooding on road networks is well known and is expected to get worse in a changing climate with more intense rainfall. For example, in Portland, USA under one climate change scenario, road closures due to flooding could increase time spent travelling by 10% (Chang et al., 2010). The impact of an increased number of flooding episodes, due to climate change, on road networks has also been modelled by Suarez et al. (2005) for the Boston Metropolitan area, USA. Their results show that delays and trip-time losses could increase by 80% and 82% respectively, between 2000 and 2100 (Suarez et al., 2005).

1.3. Identification of vulnerable roads and areas

Meeting legislative timeframes for high-priority incidents set by governments requires not only identifying roads immediately at risk of flooding, but also the wider cascading impacts of road closures. Research has focused on the former to evaluate road vulnerability and identify 'strategic' roads. For example, Koetse and Rietveld (2009) suggested that identifying the most vulnerable locations to flooding in a regional road network, as well as those routes that are critical for the operation of the network and accessing facilities such as hospitals, is a crucial part of developing an adaptation strategy. The capacity of the road network to cope with natural hazards such as flooding can be examined using resilience methods, where the redundancy of road links is studied, using the structure of the network and the number of alternative paths when one route is disrupted (Lhomme et al., 2013). Naulin et al. (2013) used a simple rainfall-runoff model to identify roads vulnerable to flooding at the regional scale, validated against observed inundation, focusing on vulnerability rating in ungauged locations. In addition, it is important to note that certain road networks in a city have greater importance in terms of maintaining access between different locations. Recently, studies have established a hierarchy of road network connections to model the impact of loss of important linkages (Albano et al., 2014; Balijepalli and Oppong, 2014). For instance, Albano et al. (2014) found using this method for Ginosa, Italy, that those roads close to health facilities, linking main parts of the town, or with no alternatives were given a high importance in terms of the operation of the network. Using this approach meant that decision makers could identify flood hotspots on the road network which may require prioritisation for risk reduction measures (Albano et al., 2014).

Whilst flood hotspots in a road network may be readily identified, whether a flooded road "hotspot" will translate into wider impacts what will affect emergency response requires further investigation as impacts are often not at the immediate vicinity of a flooded road but can manifest in a much wider context. Research on the wider impacts of road closure due to flooding and its implications for emergency responders' strategic planning and operation has been limited. A few studies have been undertaken for evacuation modelling during flooding. For example, Dawson et al. (2011) developed a multi-agent based model to guide evacuation planning during storm surge flood events, focusing on estimating the vulnerability of individuals to flooding under different conditions (e.g. storm surge, defence breach, flood warning times and evacuation strategies). Yang et al. (2015) developed a model for evacuation planning by coupling routing algorithms with numerical modelling outputs (flood extent). Moreover, a recent study by Andersson and Stålhult (2014) undertook network analysis to determine the shortest routes from hospitals to various administrative regions in the Manila city, Philippines, and the effect that floods of various magnitude had on these routes. Simi-

larly, Yu et al. (2015) and Green et al. (2017) evaluated the flood resilience of emergency responders in the City of Leicester using readily available scenario-based flood risk maps generated by the Environment Agency and a GIS-based service area approach, and focus on service area. Previous studies of flood impacts on emergency response focus on design flood events and usually take a scenario-based approach (e.g. Dawson et al., 2011; Yu et al., 2015; Green et al., 2017). As far as the authors are aware, no studies have coupled flood modelling of real events with network analysis to evaluate the wider impacts of flooding on emergency provision to vulnerable populations, despite recent advances in numerical weather prediction, hydrological and hydraulic modelling. Nonetheless, flood footprints generated by flood modelling can provide useful information for defining restrictions within network analysis. Mapping and metrics combined with network analysis tools can provide both strategic and operational support for decision making, in the context of legislated times for the emergency response.

This study describes the development and application of a method that couples numerical modelling of flood inundation with geographical analysis of service provision by the UK Ambulance Service and Fire & Rescue Service. The method will be demonstrated using two flood events in the City of York, with a focus on identifying the vulnerability of care homes and sheltered accommodation during flood events, given the 8- and 10-min response times for high-priority, life-threatening incidents. Following sections detail the method of coupling, the study area, events studied and modelling approaches used. This is followed by an analysis of travel times and service areas with and without flooding, then a discussion of the headline findings and conclusions, including opportunities for further research.

2. Method of accessibility mapping for emergency response during flooding

2.1. Overview

The method couples recent advances in flood modelling with two approaches to accessibility mapping. An overview of the approach is depicted in Fig. 1.

Recent developments in hydraulic modelling have driven fundamental changes in the approach to flood risk assessment, due mainly to: (i) increased availability of high-resolution topographic

data from airborne platforms; and (ii) rapidly growing computing power. The approach to modelling has shifted from one-dimensional finite-difference schemes which solve simplified forms of the Saint-Venant equations to two-dimensional finite-difference and finite-element flood inundation schemes (Bates and De Roo, 2000; Yu and Lane, 2006a, 2006b; Fewtrell et al., 2008; Neal et al., 2009). Recent developments in data capture techniques (for example, LiDAR) provide high-resolution and high-accuracy data, initiating a rapid shift from a data-poor to a data-rich and spatially complex modelling environment (Bates et al., 2003), including for urban areas. Indeed, for most applications, topographic data availability is no longer a limiting factor. As a result, high-resolution modelling of urban flooding has been undertaken by a number of studies (e.g. Yu and Lane, 2006a, 2006b; Fewtrell et al., 2008; Mignot et al., 2006; Yin et al., 2016a,b). Street-level, fine resolution flood footprints obtained using numerical models enable detailed evaluation of flood impacts on urban transport networks that, in turn, determines accessibility during flooding. This is not limited to fluvial flooding, but also enables surface water flood and impacts modelling (e.g. Yin et al., 2016b).

We quantify accessibility using two metrics: (i) area coverage from emergency response nodes (i.e. Fire & Rescue Station; Ambulance Station) within the legislated timeframes (i.e. 8-min for the Ambulance Services and 10-min for Fire & Rescue Services); and (ii) shortest time taken from an emergency response node to vulnerable populations, again evaluated against the legislated targets. We employ the service area method to map the spatial coverage of the emergency services within the specified response timeframes. Service area mapping is an established field of network analysis. It is useful especially for evaluating service coverage by organisations from their operation sites such as stores, warehouses and distribution centres.

2.2. Data requirements

To undertake service area analysis, the first step is to establish the road network connectivity for a city. In the UK, this is defined by the Ordnance Survey Integrated Transport Network (ITN) which contains a set of pre-defined rules of network connectivity (e.g. speed limit, turn restriction and one-way traffic), which is fundamentally the same set of data used by satellite navigation for autonomous geo-spatial positioning. Similar information is available in other countries although they might not be readily accessible. The second dataset is the 'facility' layer, which contains the locations of emergency responder stations. Spatial coverage of a city from service stations as well as shortest travel times between individual stations to vulnerable populations can then be mapped, with or without the consideration of traffic or hazards such as flooding.

To evaluate accessibility during flooding, flood areas obtained from hydrodynamic models can be used as polygon 'barriers' (flood restriction) within the ITN. A depth and/or velocity threshold needs to be defined for a flooded area to be treated as a flood restriction. We used a threshold depth of 25 cm. This was based on advice from Smart Driving (2016) which suggests that water greater than 25 cm deep may be dangerous to drivers. The same value was used by Dawson et al. (2011) and Green et al. (2017) who assumed that depths >25 cm could cause drivers to lose control of their vehicle. Ideally, velocity would also be considered because fast-flowing water may pose greater threats to vehicles.

Following Green et al. (2017), a three-step, quality control process was applied to further process flood restrictions predicted by the modelling. The stages involve: (i) removing isolated pixels that intersect marginally with a road; (ii) removing any predicted inundations with areas less than 100 m², assuming that vehicles can

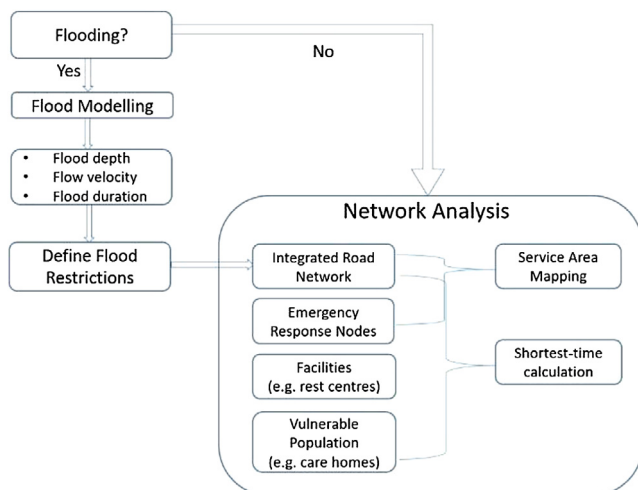


Fig. 1. Method for evaluating a city's emergency accessibility by coupling flood modelling with network analysis.

navigate puddles and; (iii) visual inspection to establish links to places where bridges over a water body were not represented in the digital elevation model. In cities where an overpass route intersects with an underpass route, links should only be established for the overpass route rather than the underpass if the latter is predicted as flooded. This is not a concern for York where there are no such cases in the city and we only had to re-establish links representing bridges over rivers.

3. Implementation of the method

3.1. Case study site, data availability and flood events

Situated on the low-lying confluence of the River Ouse and the River Foss, with a population of 202,000 in 2011 and an area of 272 km², the City of York, UK has a long history of flooding (Fig. 2). Mean annual rainfall between 1981 and 2010 was 626 mm, with August being the wettest month (62 mm) (Met Office, 2016). The non-tidal reach of the River Ouse (which eventually runs through the City of York, see inset in Fig. 1) comprises a wide, sinuous, low-land channel that flows through the Vale of York. The reach receives the majority of its water from three sub-catchments: the Swale; the Ure; and the Nidd (Yu, 2005). In these river catchments, there has been a tendency to higher magnitude and more frequent flood events since the 1940s, with the exception of a period of notably lower peak flows in the early 1970s (Lane, 2003).

Since the year 2000, there have been three major fluvial floods in the city, including an event in autumn 2000, winter 2012, and on 26 December 2015. The 2000 peak water level at the upstream Skelton Gauging Station is the highest on record (6.784 m), exceeding the 2012 and 2015 event by 23 cm and 15 cm respectively. But the 2015 event is marked as the worst flooding for York in recent decades due to the associated flooding by the River Foss. Most flood defences in the urban areas were built in the early 1980s and 1990s, and designed to a 1 in 100-year Standard of Protection. However, the actual standard of protection is expected to have degraded given recent events (City of York Council, 2013). An important part of the city's flood defences is the Foss Barrier which was built in 1998 at the Ouse/Foss confluence, and is designed to prevent water from backing up from the River Ouse. The barrier has been largely effective in protecting the city from flooding. However, it was raised during the 2015 event because of control room flooding, in addition to the inability of the pumping stations to cope with high flows in the River Foss. This in turn caused unprecedented flooding of the city centre and serious delays to emergency service response times (Environment Agency, 2016).

In addition to river flooding, York is also vulnerable to surface water flooding, as witnessed in 2007, when large parts of northern England experienced heavy rainfall due to slow-moving low pressure systems (Hanna et al., 2008). Localised flooding occurred between 24 and 25 June at various locations in the city, many of which do not usually experience river flooding (City of York Council, 2007). This prompted a review of the surface water infrastructure and maintenance strategies in York, including an investi-

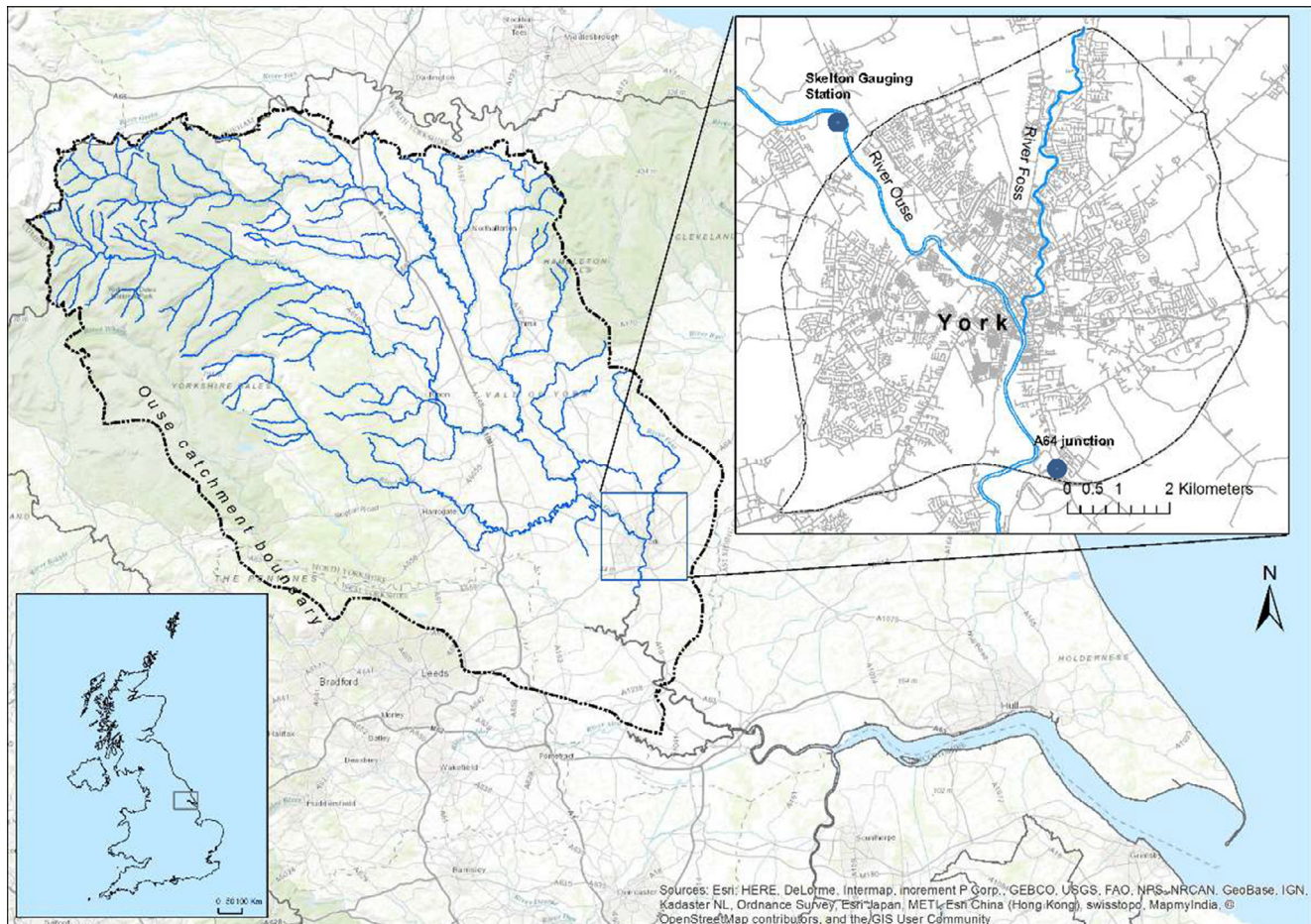


Fig. 2. Geographical location of the City of York. Inset at the top right shows the modelling site, including the two rivers modelled, the upstream gauging site (Skelton Gauging Station) and downstream modelling boundary (A64 junction).

gation of the hotspots that were flooded in 2007 (City of York Council, 2012). However, many of these areas experienced flooding again during heavy rainfall on the 8 August 2014 (an event investigated below). This renewed attention on the Council's gully cleaning service (York Press, 2016). Our study uses the 2015 fluvial flood and the 2014 pluvial flood as events for evaluating the impacts of flooding on emergency service provision for the city. Digital elevation data used in both the fluvial and pluvial modelling were derived from a 1 m resolution LiDAR dataset and resampled to a resolution of 10 m to cover the whole city area.

Locations of care homes in York were obtained from the City of York Council and a list of sheltered accommodation was provided by Housing Care (2015). These were geo-referenced into a GIS platform, along with the locations of fire stations, ambulance stations and hospitals (Fig. 3). The Ambulance Service position rapid response vehicles either at Ambulance stations or at York Hospital. Therefore, both the Ambulance stations and York Hospital were used as nodes in the accessibility analysis.

3.2. Fluvial flood modelling of the 2015 event

The fluvial modelling site extends from the A64 road bridge upstream to Skelton Gauging Station (Fig. 2). The 1D/2D coupled version of FloodMap (Yu and Lane, 2006a,b) was used to simulate the 2015 fluvial flood. River flow was simulated with the full solution of Saint-Venant equations and floodplain flow routing with 2D inertial formation (Bates et al., 2010). The 1D river-flow model is based on the fixed bed algorithm of Abbott and Basco (1989) and solves the one-dimensional St. Venant equations for unsteady flow using the Preissmann Scheme, also known as an implicit box scheme (Yu, 2005). The model was calibrated for the same site using the 2000 fluvial flood event by Yu (2005) and demonstrated good predictive skill. Cross-sectional geometries were obtained from the Environment Agency. A simplified geometry was assumed based on a prismatic channel with uniform rectangular cross-section shape. In general, cross-sections were taken every 200 m along the river channel. More cross-sections were used in meanders and a cross-section was taken immediately upstream and downstream of each bridge. In total, 80 cross-sections were used to represent the 1D channel in the model.

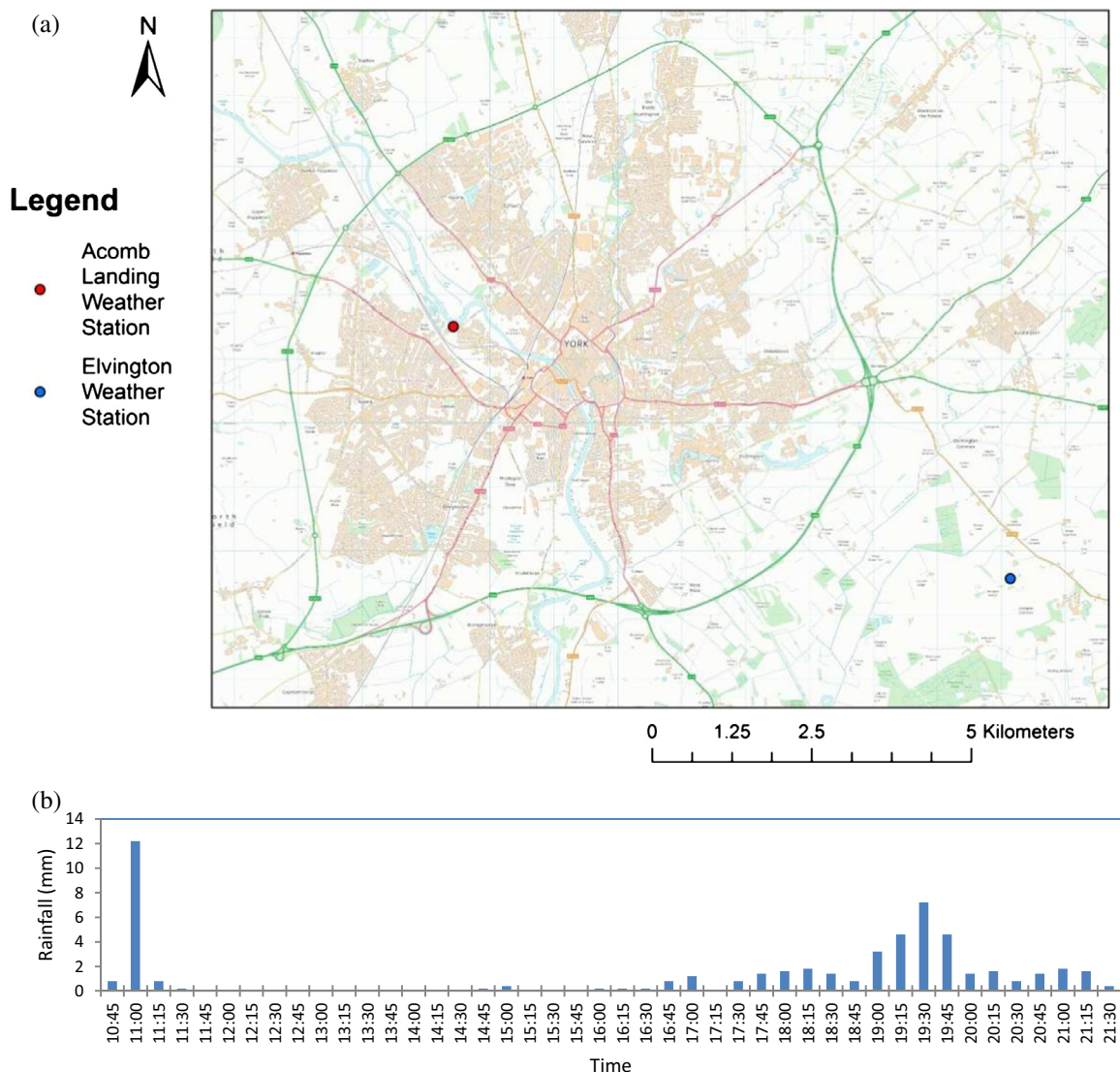


Fig. 3. (a) Map of the two weather stations in the York area; and (b) Rainfall hyetograph for the 8th of August 2014 from the Acomb Landing weather station. Background map source: EDINA Digimap (2015).

Upstream fluvial boundary conditions were provided by a 15-min stage hydrograph recorded at the Skelton gauging station, for the period 05:15 on 26 December 2015 to 00:00 29 December 2015. This record has a single peak of 6.634 m, the second highest on record, just 15 cm below the 2000 event peak. Hydraulic normal depth was assumed at the downstream boundary. Roughness values were adjusted in conjunction with the temporal and spatial coefficients used in the 1D model solution (Preissmann Scheme) to allow model calibration. As cross sectional data of the River Foss and its tributaries were unavailable and discharge data were incomplete, the 1D model excludes these elements of the drainage network. Rather, the bank-full river level is specified at the upstream gauging site of the River Foss and the model allows flow to route along the original LiDAR topography and a spin-up period was introduced into the model to allow the River Foss to reach near bank-full depth before introducing the 2015 flood hydrographs at the upstream inflow boundary of the River Ouse. To represent the Environment Agency's decision to lift the Foss barrier, flow was allowed to back up from the River Ouse to River Foss. As such, the exact timing of flood inundation predicted in the vicinity of River Foss may not be accurate. However, it is expected that the magnitude of flooding is adequately represented as recorded flow data were used in the upstream of River Foss. The recorded flood extent for the event was obtained from the Environment Agency and is used to validate the model predictions. Surface flow routing takes an inertial formulation (Bates et al., 2010), but with a slightly different approach to the calculation of time step. Neglecting the convective acceleration term in the Saint-Venant equation, the momentum equation becomes:

$$\frac{\partial q}{\partial t} + \frac{gh\partial(h+z)}{\partial x} + \frac{gn^2q^2}{R^{4/3}h} = 0 \quad (1)$$

where q is the flow per unit width, g is the acceleration due to gravity, R is the hydraulic radius, z is the bed elevation, h is the water depth and n is the Manning's roughness coefficient. Discretizing the equation with respect to time produces:

$$\frac{q_{t+\Delta t} - q_t}{\Delta t} + \frac{gh_t\partial(h+z)}{\partial x} + \frac{gn^2q_t^2}{h_t^{7/3}} = 0 \quad (2)$$

To further improve this, one of the q_t in the friction term can be replaced by $q_{t+\Delta t}$ and this gives the explicit expression of the flow at the next time step:

$$q_{t+\Delta t} = \frac{q_t - gh_t\Delta t \left(\frac{\Delta(h_t+z)}{\Delta x} \right)}{\left(1 + gh_t\Delta t n^2 q_t / h_t^{10/3} \right)} \quad (3)$$

The flow in the x and y directions is decoupled and take the same form. Flow is evaluated at the cell edges and depth at the centre.

3.3. Surface water flood modelling of the 2014 event

The heavy rainfall event of 8 August 2014 was chosen for surface flood modelling as this represented one of the largest rainfall totals in the city in recent years and caused widespread disruption to the transport network. Two rain gauges are present in the area, one at the Acomb Landing weather station (located within York), the other at the Elvington weather station (~7 km to the southeast of the city in a rural site) (Fig. 4a). The rainfall hyetograph for Acomb Landing is shown in Fig. 4b. Radar rainfall data were obtained from the Met Office Centre for Environmental Data Analysis (NIMROD System) at a resolution of 1 km and 15-min interval (Met Office, 2009). Rainfall hyetographs were created by extracting radar values coinciding with each weather station location. The radar data were compared with the rainfall hyetographs observed

at the two weather stations (Fig. 4a), using the Root Mean Squared Error (RMSE) and difference of the peak precipitation rate (PDIFF) (e.g. Yilmaz et al., 2005; Dawson et al., 2007). Rainfall inputs used in the modelling were derived from the 1 km resolution Radar data.

FloodMap-HydroInundation2D (Yu and Coulthard, 2015) was used to model the surface water flooding process. The model was based on FloodMap (Yu and Lane, 2006a,b) which integrates hydrological parameters such as evapotranspiration, infiltration and drainage with surface flow routing. Previous fine scale simulations (at 2 m resolution) have been performed with the model to evaluate the impact of land subsidence in downtown Shanghai (Yin et al., 2016a), and its impact on the urban transport network (Yin et al., 2016b). A detailed description of process representation can be found in Yu and Coulthard (2015). Here we present the key hydrological process represented in the model.

Infiltration is calculated via the Green-Ampt equation, with saturated hydraulic conductivity and capillary potential as the key parameters, linked to time and porosity, taking the following form:

$$f(t) = K_s \left(\frac{\phi_f + h_o}{z_f} + 1 \right) \quad (4)$$

where K_s is the hydraulic conductivity of the soil at field saturation, ϕ_f is the capillary potential across the wetting front, h_o is the ponding water on the soil surface, and z_f is cumulative depth of infiltration. Hydraulic conductivity is often used as a calibration parameter in hydrological studies.

For hydro-inundation modelling, the amount of evapotranspiration during storm and flooding conditions is in the order of 3–5 mm/day, a small amount compared to infiltration and drainage processes. Evapotranspiration is calculated using a simple seasonal sine curve for daily potential evapotranspiration (Calder et al., 1983) with the equation below:

$$E_p = \bar{E}_p \left[1 + \sin \left(\frac{360i}{365} - 90 \right) \right] \quad (5)$$

where \bar{E}_p is the mean daily potential evapotranspiration and i is the day of the year.

For this study, evapotranspiration was set at 3 mm/day – a negligible value compared to the infiltration rate and drainage capacity (assumed to be 70 mm/day for a 1 in 30-year event in the UK). Given the spatial and temporal heterogeneity of the radar-derived precipitation, the model was further developed for this study to allow distributed precipitation datasets to be used as inputs.

Hydraulic conductivity is a key parameter in surface water flood modelling and it is typically estimated based on soil properties. Slowly permeable clayey soils are the dominant soil types in the study area, with some areas of loamy and clayey soils with impeded drainage. Hydraulic conductivity was estimated based on USDA Natural Resources Conservation Service (2015) which gives a saturated hydraulic conductivity rate between 0.0015 and 0.005 m/h for clayey soils. Therefore, multiple simulations were undertaken with a range of hydraulic conductivity values between 0.001 and 0.005 m/h.

Removal of water by the drainage system is represented in the model by the design capacity of the storm sewer system, which is normally associated with a rainfall event of a certain magnitude and return period. York has a sewer system with design capacity of 1-in-30 years (City of York Council, 2007) corresponding to 70 mm of rainfall over a 24-h period (Coulthard et al., 2007). However, it was reported that due to debris blockage (York Press, 2016), the system would unlikely have performed to its design capacity during the event. This is not surprising as the capacity of urban drainage systems tends to degrade over time (e.g. Coulthard and Frostick, 2010) and can be affected by debris blockage. Therefore,

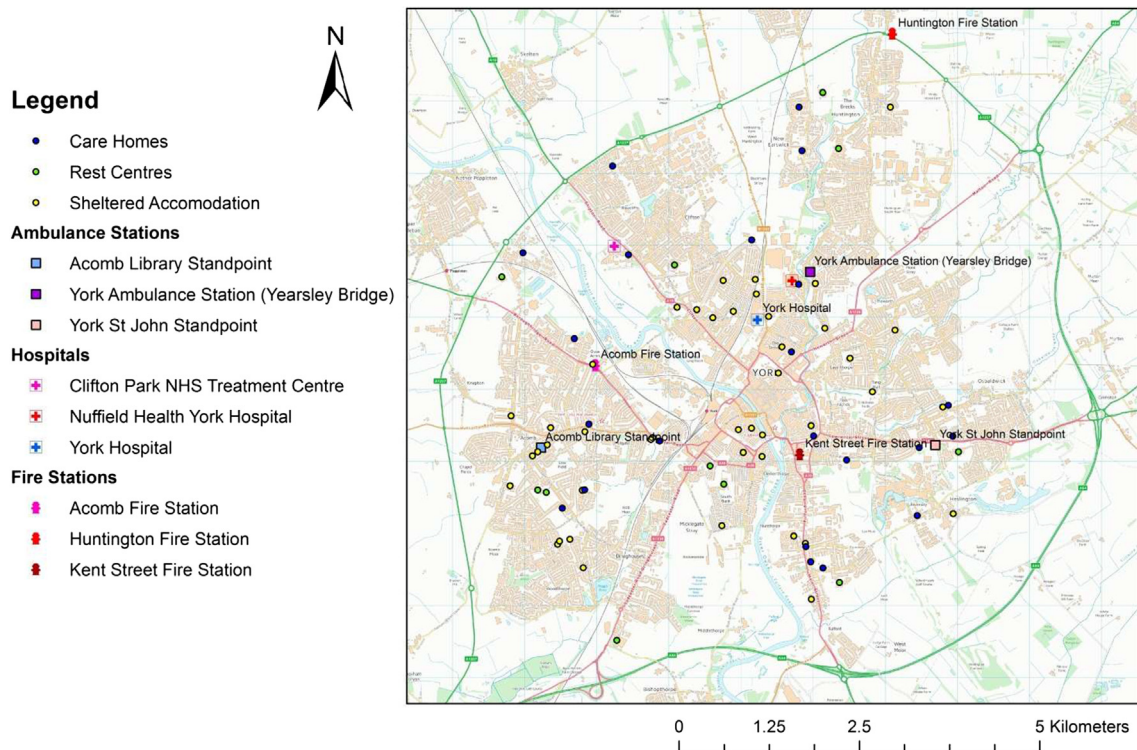


Fig. 4. Locations of care homes, sheltered accommodation locations, emergency service response locations, and hospitals, in York. Background map source: EDINA Digimap.

drainage capacity values of 30 mm/day, 50 mm/day and 70 mm/day were chosen in the calibration to test sensitivity to drainage capacity.

4. Results and discussion

4.1. Baseline simulations

We first evaluated the accessibility of the Ambulance and Fire & Rescue Services under non-flood conditions assuming that maximum speed limits were achieved with no restrictions in the road networks. The spatial coverage of the Ambulance Service, and Fire & Rescue Service within the legislated timeframe (i.e. 8- and 10-min respectively) for high-priority, life-threatening incidents was evaluated. Fig. 5 suggests good coverage of the city by the Fire & Rescue Service to deal with high-priority life-threatening incidents. Care homes and sheltered accommodations were all shown to be accessible within a 10-min radius of the Fire & Rescue nodes. Additionally, areas within the city's ring roads were all within reach. In comparison, the Ambulance Service nodes were found to be less well located for achieving their 8-min response time for all locations in the city.

4.2. Fluvial flood modelling of the 2015 event

Fluvial flood modelling was calibrated with the 2000 event by Yu (2005). The same parameters were used in the present simulation. In the absence of observation data which were provided by the Environment Agency after the simulation was set up and run, further calibration was deliberately not undertaken. The results show a good level of agreement (with a *Fit* statistic of 0.79) in most places across the city suggesting that the parameter set used in the 2000 event is equally applicable to the 2015 event (Fig. 6). In location A, the site of a Yorkshire Water Treatment Plant, the simulated and observed flood extents match well. In the majority of other

locations, including the area adjacent to the River Foss, the model performs equally well.

However, there is an overestimation of flood extent at point B and underestimation at point C. We evaluated the prediction based on whether the discrepancy reflects a false 'barrier' (flood restriction to traffic) or misses a true barrier hence introducing errors into the accessibility analysis. Flooded roads in location B were not transit roads so this would not have an effect on accessibility calculation of the model. The underestimation of flood extent at location C was attributed to an underground culvert beneath the adjacent embankment that was not represented by the DEM. This could be corrected by lowering the DEM to re-establish fluvial connectivity. However, as the culvert leads to a storage area (and the underestimation does not affect the accessibility analysis), rather than correcting the discrepancies through calibration, we chose to maintain the uncalibrated nature of the simulation to demonstrate that in situations where validation data may not be immediately available, analysis can still be useful to support operational decision making in emergency response. The simulated water depth was used to define polygon barriers where a pixel with a depth greater than 25 cm intersects with a road in the ITN. As mentioned before, a flood threshold extent less than 100 m² was used to remove isolated pixels, as well as conducting a visual inspection to establish connectivity surrounding bridges and overpasses.

4.3. Accessibility mapping for the 2015 event

The overall accessibility of the city for emergency response nodes (Ambulance Service; Fire & Rescue Service) was mapped with the modelled and observed flood extents as barriers respectively. The accessibility maps shown in Fig. 7 demonstrate good agreement between accessibilities derived from modelled and observed flood extent, especially in places where flood modelling was undertaken (e.g. along the River Ouse and River Foss). In the areas enclosed by rectangles there are notable discrepancies and

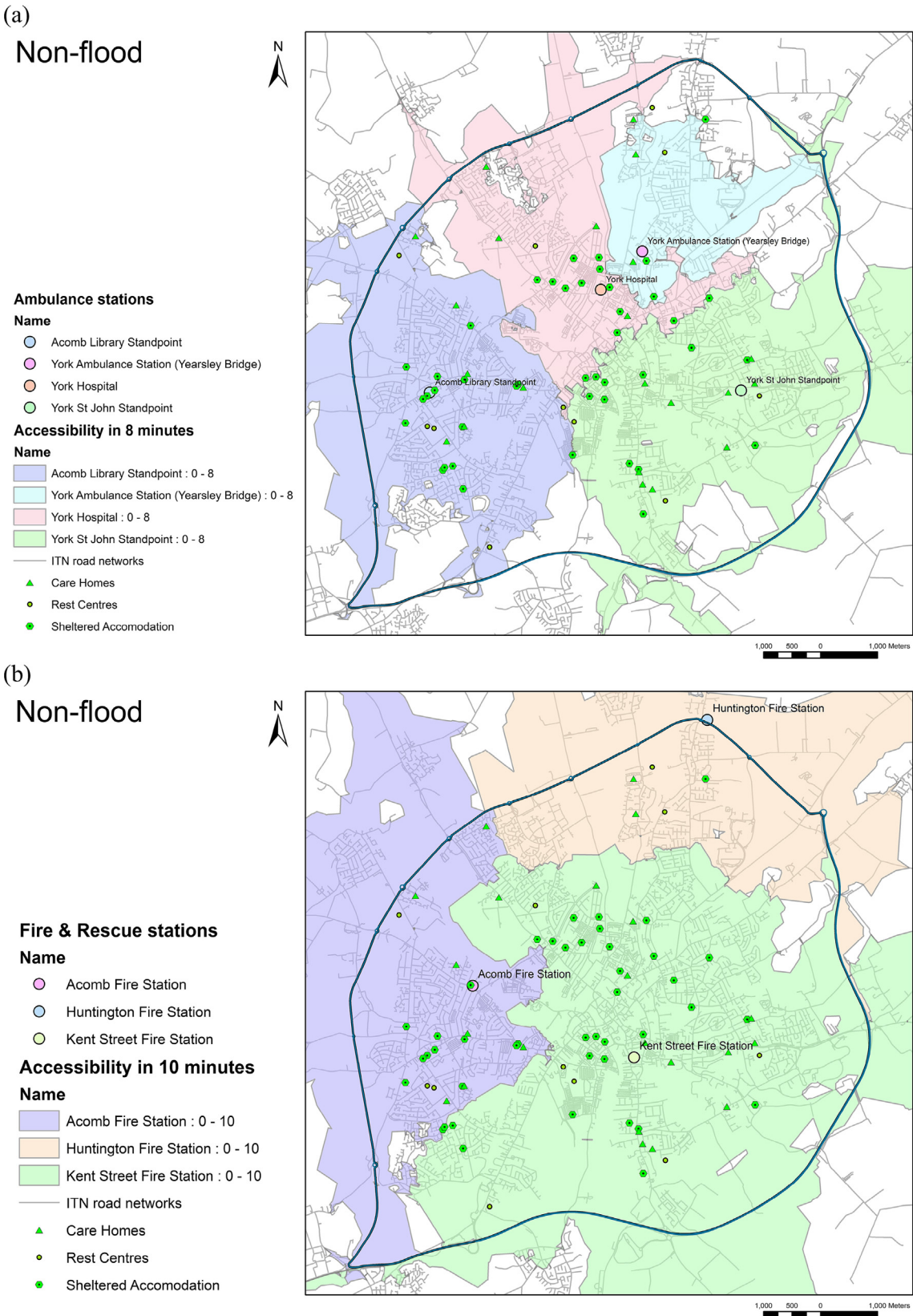


Fig. 5. Accessibility for emergency responders under normal conditions within the legislation timeframe for high-priority, life-threatening incidents, assuming normal traffic: (a) 8-min for Ambulance Service; and (b) 10-min for Fire & Rescue Service.

these are outside of the simulation domain where flood modelling was not undertaken due to lack of data.

For the Ambulance Service, there is a notable reduction in the service area for high priority, 8-min response for York Hospital

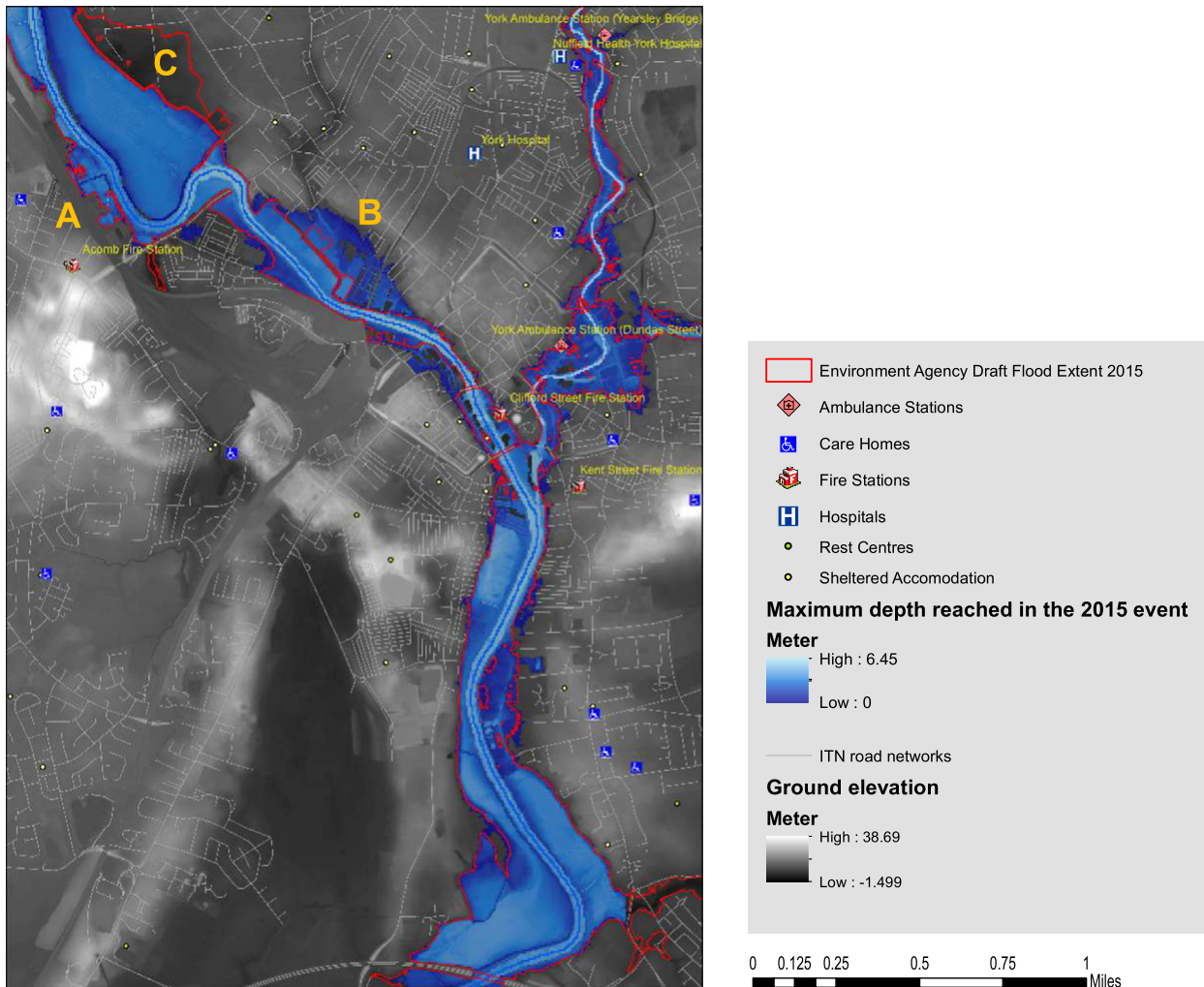


Fig. 6. Maximum depth simulated for the 2015 event. Red outline is the observed flood extent (draft Environment Agency, 2016). F statistic is 79%. Clifford Street Fire Station did not operate during 2014 and 2015, hence was not used. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which is located to the east of the River Foss. During the event, the station no longer had access to areas west of River Foss. The two stations most affected were the York Ambulance Station and York St. John Standpoint which see large areas losing service within an 8-min timeframe, especially when the observed flood extent is used in the analysis.

The comparison demonstrates that in situations where observed data may not be immediately available, accessibility analysis, aided by numerical modelling, even when calibrated using minimal data, can provide an adequate assessment of York's accessibility to emergency responders, during flood events. Scenario-based assessment can also be achieved with numerical modelling to evaluate accessibility under various scenarios.

Table 1 summarizes the percentage changes in service area coverage for individual emergency nodes and the total changes for Fire & Rescue (Table 1a) and Ambulance (Table 1b) stations, with both the modelled and EA-observed inundation extents as barriers in the ITN. A non-overlap method was used to calculate service area in our analysis. This means that a place in space is allocated to the nearest node so, when flooding is taken into account, there are stations gaining service areas from those that are losing. For example, the Fire & Rescue Service, Kent Street Fire Station gained 39% coverage area when compared to a non-flood scenario. The reduction of service coverage ranges from 18% to 61% for the sta-

tions analysed, with the overall reductions in service area of 6% and 20% for modelled and observed floods respectively. A similar outcome can be seen in Table 1b, in which the Ambulance Service has one station gaining coverage while the other three lose coverage, with the impact of flooding introducing an overall reduction in the total areas covered by 6% and 15% for the modelled and observed flood extents respectively.

4.4. Surface water flood modelling of the 2014 event

Fig. 8 compares rain gauge and radar-derived precipitation rates over the course of the 2014 event at the two gauging stations. The temporal pattern of radar-derived precipitation rate correlates well with that of the gauged data. For the 2007 surface water flood event, the overall RMSE during the event for the Acomb Landing and Elvington stations is 0.48 mm and 0.56 mm respectively, suggesting a consistency in the overall temporal pattern for the two stations. The peak in the 2007 radar data is higher than that of the single site data, with a difference of 0.59 mm for the Elvington weather station and 0.76 mm for Acomb Landing. RMSE values for the 2014 event are higher, especially for the Acomb Landing station, largely due to the discrepancy at the onset of the rainfall event at around 10:30 am (Fig. 4). Similarly, an underestimation

Ambulance stations

Name

- Acomb Library Standpoint
- York Ambulance Station (Yearsley Bridge)
- York Hospital
- York St John Standpoint

Accessibility in 8 minutes

Name

- Acomb Library Standpoint : 0 - 8
- York Ambulance Station (Yearsley Bridge) : 0 - 8
- York Hospital : 0 - 8
- York St John Standpoint : 0 - 8

ITN road networks

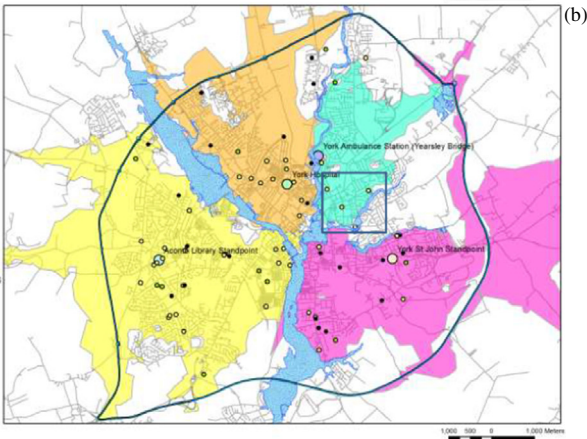
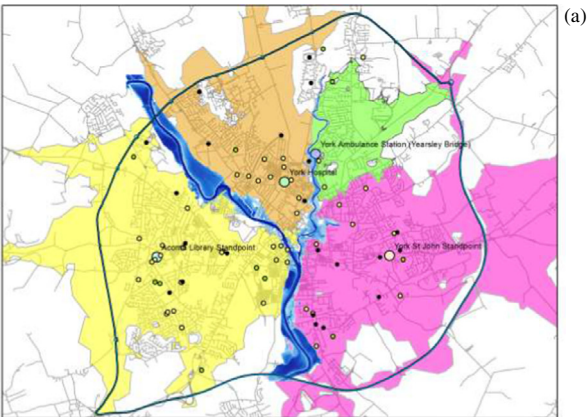
- Care Homes
- Rest Centres
- Sheltered Accomodation

Maximum depth

(m)

- High : 7.79
- Low : 0

Draft extent (Environment Agency)



Fire & Rescue stations

Name

- Acomb Fire Station
- Huntington Fire Station
- Kent Street Fire Station

Accessibility in 10 minutes

Name

- Acomb Fire Station : 0 - 10
- Huntington Fire Station : 0 - 10
- Kent Street Fire Station : 0 - 10

ITN road networks

- Care Homes
- Rest Centres
- Sheltered Accomodation

Maximum depth

(m)

- High : 7.7914
- Low : 0

Draft extent (Environment Agency)

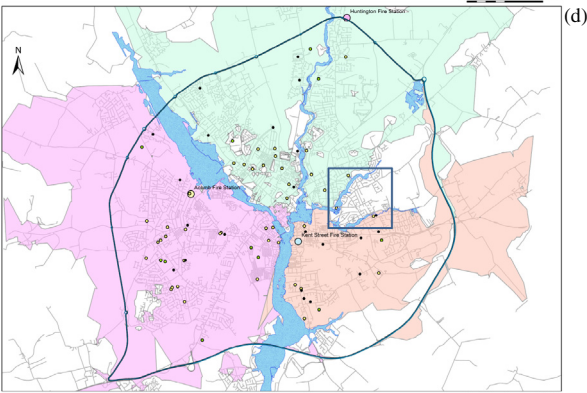
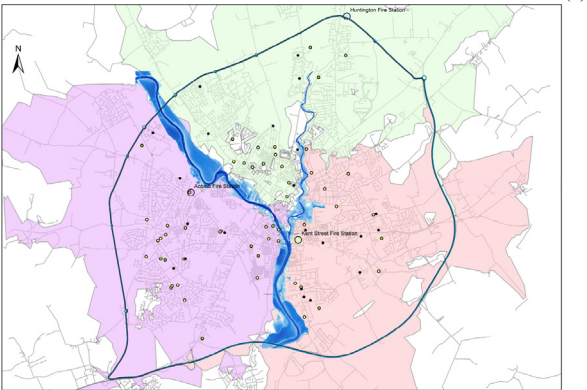


Fig. 7. Spatial coverage of individual: Ambulance Service stations within 8-min (a and b); and Fire & Rescue Service stations within 10-min (c and d) in the 2015 event. Observed (b and d) and modelled extent (a and c) are used as flood restrictions.

Table 1

Percentage change of area for (a) the Fire & Rescue Service and (b) the Ambulance Service.

Fire & rescue (10 min)	With modelled extent	With EA extent
<i>(a)</i>		
Acomb fire station	−14%	−14%
Kent street fire station	+39%	+67%
Huntington fire station	−39%	−43%
Total area	−6%	−20%
<i>(b)</i>		
Ambulance (8 min)	With modelled extent	With EA extent
York ambulance station (Yearsley Bridge)	−31%	−12%
Acomb library standby-point	+7%	+6%
York St John standby-point	−8%	−40%
York hospital	−15%	−17%
Total area	−6%	−15%

of 4.5 mm is noted in the peak radar rainfall during the onset period at Acomb Landing.

Whilst there are discrepancies between the precipitation rate derived from rain-gauges and radar for both sites and events, there is no consistent bias either between sites or events. The overall difference (RMSE) in precipitation rate suggests the discrepancy is not significant in the 2007 event for both the urban and rural sites (0.48 mm and 0.56 mm respectively). The higher discrepancy of 2.06 mm at the urban station during the 2014 event is associated with a relatively large difference at the first peak of the event. Similarly, the peak precipitation rates are marginally different, except for the urban station as the first peak at the onset is also the hye-

tograph peak during the event. Overall, there is an overestimation of the total amount of rainfall for the 2007 event based on radar rainfall. However, for the 2014 event, there is a slight underestimation in the total rainfall for the urban and rural stations respectively. The first peak difference of 4.45 mm in the 2014 event for the urban site is expected to generate less surface inundation with the radar-derived rainfall. However, as the subsequent main precipitation episode occurs around 2 h following this peak, it is estimated that much of the rainfall would not be effective and would have infiltrated into the ground or drained into the storm sewer system. Therefore, radar-derived rainfall was used in the simulation to provide precipitation inputs to the inundation model.

The effects of surface water flooding for the modelled 2014 event were spatially concentrated in the west side of the city. This area received the heaviest rainfall during this event, and also contains the majority of the surface water flooding hotspots in this area (City of York Council, 2012). Flooding resulting from this event highlighted the neglect in the maintenance of the drainage system in the hotspot areas of the city (City of York Council, 2012), with some road gullies being identified for cleaning only very recently (York Press, 2016).

Fig. 9 shows maximum depths under different hydraulic conductivity and drainage capacity values. A hydraulic conductivity value of 0.005 m/h was unable to generate surface runoff, suggesting total loss due to infiltration, drainage and evapotranspiration exceeded rainfall rate over the entire domain. When hydraulic conductivity was set to 0.001 m/h, for both drainage capacity values (30 mm/day and 50 mm/day), surface runoff was shown to occur, resulting in inundation. When considering the urban surfaces and soil characteristics of the site, a hydraulic conductivity of 0.001 m/h is a realistic infiltration capacity.

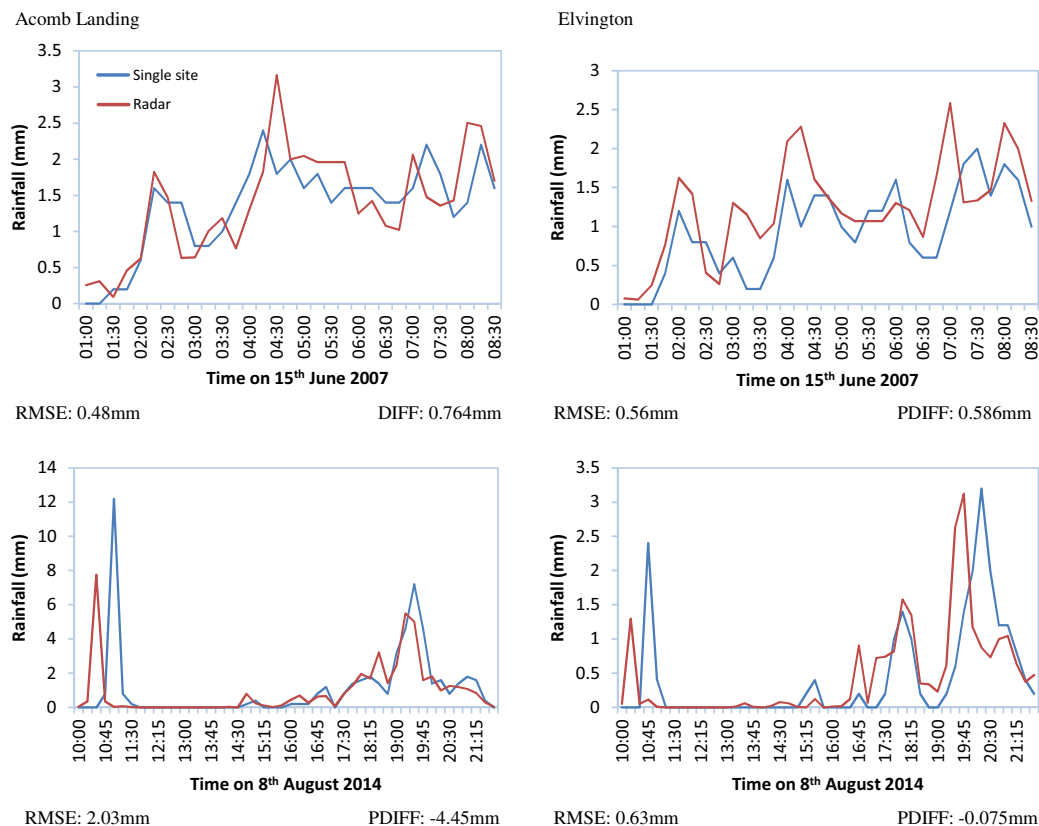


Fig. 8. Comparison of the single site and radar data rainfall hyetographs for two sites covering the York area, Acomb Landing and Elvington, and also for two heavy rainfall events (15th of June 2007 and 8th of August 2014).

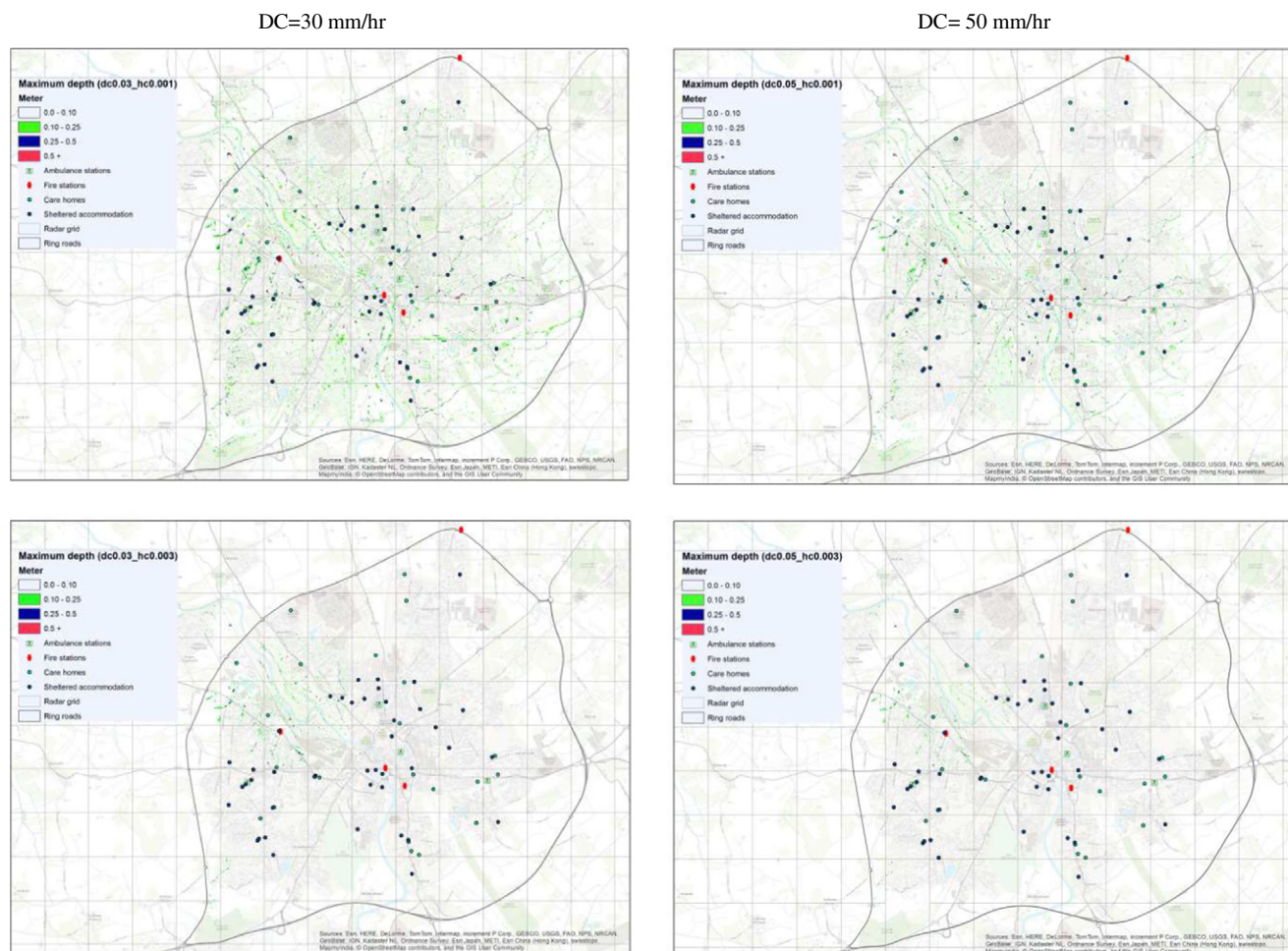


Fig. 9. Surface flood model calibration using various combinations of hydraulic conductivity (HC) and drainage capacity (DC) to generate surface run off. Maximum water depth for the modelled rainfall event (8 August 2014) is shown. The pixelised prediction with HC = 3 mm/h reflects the resolution of the radar data (1 km by 1 km).

No flooding was officially recorded for this event. However, there are reports in some media sources. Therefore, photographs and textual information was used to verify the areas predicted to be inundated (Fig. 10). The simulation with drainage capacity set to 30 mm/day and hydraulic conductivity 0.001 m/h generates the closest representation of what was reported by the media.

4.5. Accessibility mapping for the Ambulance Service in the 2014 event

For the 2014 event, the total 8-min service area coverage (Fig. 11) reduces to 48 km² from 96 km² under 'normal' conditions (Fig. 5). This is due to a flood restriction ('barrier' in the network analysis) blocking access from the Acomb Library ambulance standpoint and, as a result, this station has no service area. Furthermore, the whole area of Acomb, Foxwood and Woodthorpe are unable to be reached within 8 min from the other stations. When the flood restriction blocking the Acomb Library standpoint was removed the total service area coverage improves from 48 km² to 64 km² and many locations that were previously inaccessible can be reached within 8-min (Fig. 11). However, there was still reduced service coverage in Rawcliffe, to the northwest of York, even when this restriction was removed, caused by flooding of other roads.

The modelled 2014 surface water flood event causes widespread increases in ambulance response times to care homes (Fig. 12) and sheltered accommodation (Fig. 13). Most of the increases may be attributed to the lack of access from the Acomb

Library Stand-point. For example, 7 out of the 22 care homes (32%) have a modelled response time that is above the 8-min threshold. When the Acomb Library flood restriction was removed from the analysis, this reduced to only two above the defined threshold (Fig. 12). Similarly, 15 out of the 43 sheltered accommodation (35%) have response times over 8-min during the modelled 2014 flood event. When the flood restriction at the site was removed, this was also reduced to two (Fig. 13). This could be achieved by (i) pumping water away from the access roads, or (ii) repositioning the vehicle stand-point to a location with better access and no flood restrictions. Conversely, the impacts of the 2014 flooding on Fire & Rescue Service were limited and all vulnerable nodes were modelled to be accessible within 10-min by all the three Fire & Rescue stations operating within the city during the event.

Arguably, the relatively low magnitude of past surface water flood events in York did not result in widespread unmanageable disruptions to emergency responders, compared to other events such as the 2007 summer flood in Hull. The June 2007 floods which affected many parts of the UK, including York, prompted a review of flood risk management, focusing on the resilience and vulnerability of critical infrastructure in addition to emergency response, planning and recovery (Pitt, 2008). When compared to the greater than 1 in 200-year return period estimated for the Hull event at that time, the June 2007 flood in York was estimated to be 1 in 20 years (Hanna et al., 2008). Calls to the Humberside Fire and Rescue Service (HFRS) which operates in the city reached 100 per hour

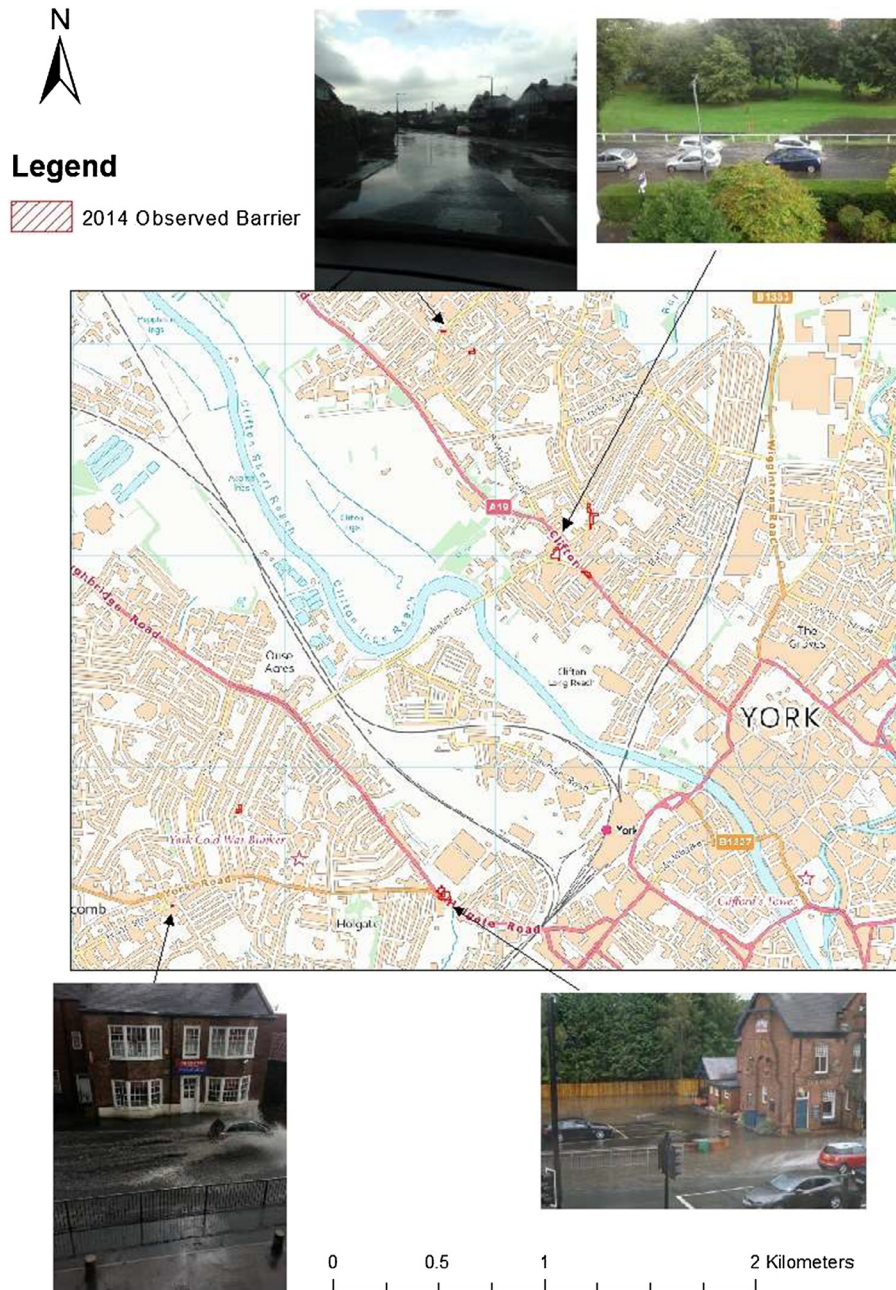


Fig. 10. Polygon barriers produced from the surface water flood modelling results and photographs of these locations on the 8 August 2014 (York Press, 2014a,b).

on the 25 June 2007 (Coulthard et al., 2007). Surface water flooding in other locations have also raised concerns about the travel times by emergency responders. For example, residents of Heywood near Manchester argued that the Fire & Rescue Service was too slow in closing inundated roads and pumping away floodwater during the surface water flooding in 2004 and 2006 (Douglas et al., 2010), suggesting that a faster response is needed to manage accessibility via critical infrastructure.

4.6. Further considerations

Emergency responders may choose to navigate across flooded roads and our 25 cm threshold may be too conservative. However, if flooding is extensive and dynamically evolving, it will be challenging to determine the actual water depth at distance. Sub-

merged obstacles (such as surcharged manholes) may also pose serious threats to personnel and vehicles. Other factors may further add to the actual travel time such that the response time estimates generated herein are likely to be at the lower end of “real-world” situations. First, the analysis does not take into account time to answer emergency calls and dispatch emergency vehicles. For example, the London Fire Brigade aims to answer emergency calls in 7 s and dispatch the first fire engine within 100 s (London Fire Brigade, 2014). If this information was available for York, it could be added to the modelled travel times to make a more realistic response time. However, this may be difficult to incorporate into the model for flood events, where emergency responder resources are likely to be under greater strain.

Second, the analysis does not take into account traffic volume, day of the week or time of day. This could be addressed by incor-

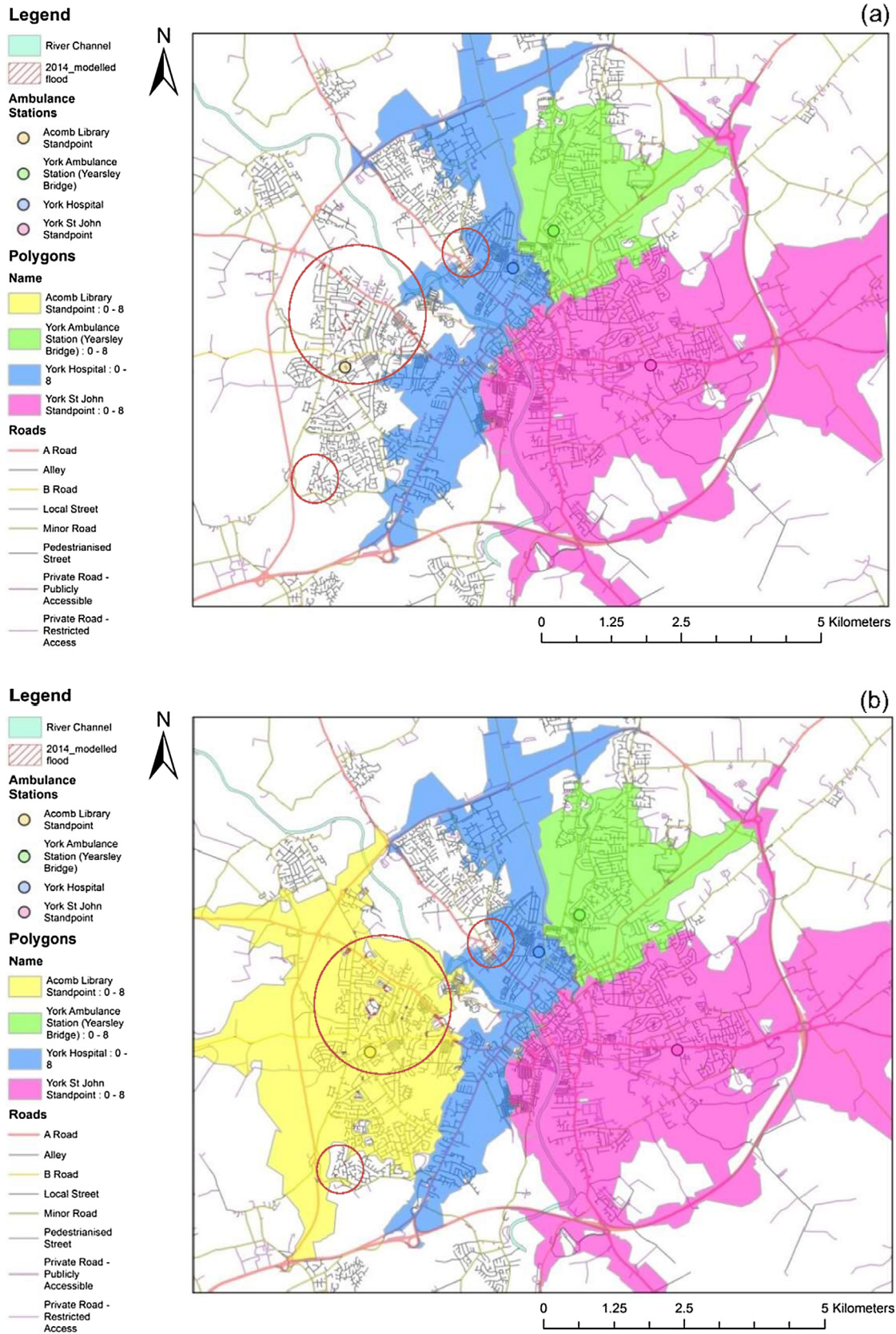


Fig. 11. Service area coverage, in an 8-min time period, for the Ambulance Service in York, with the 2014 modelled flood inundation area with (a) no service area for the Acomb Library Standpoint, and (b) the barrier to this station removed. Circled areas are flood hot spots during the event.

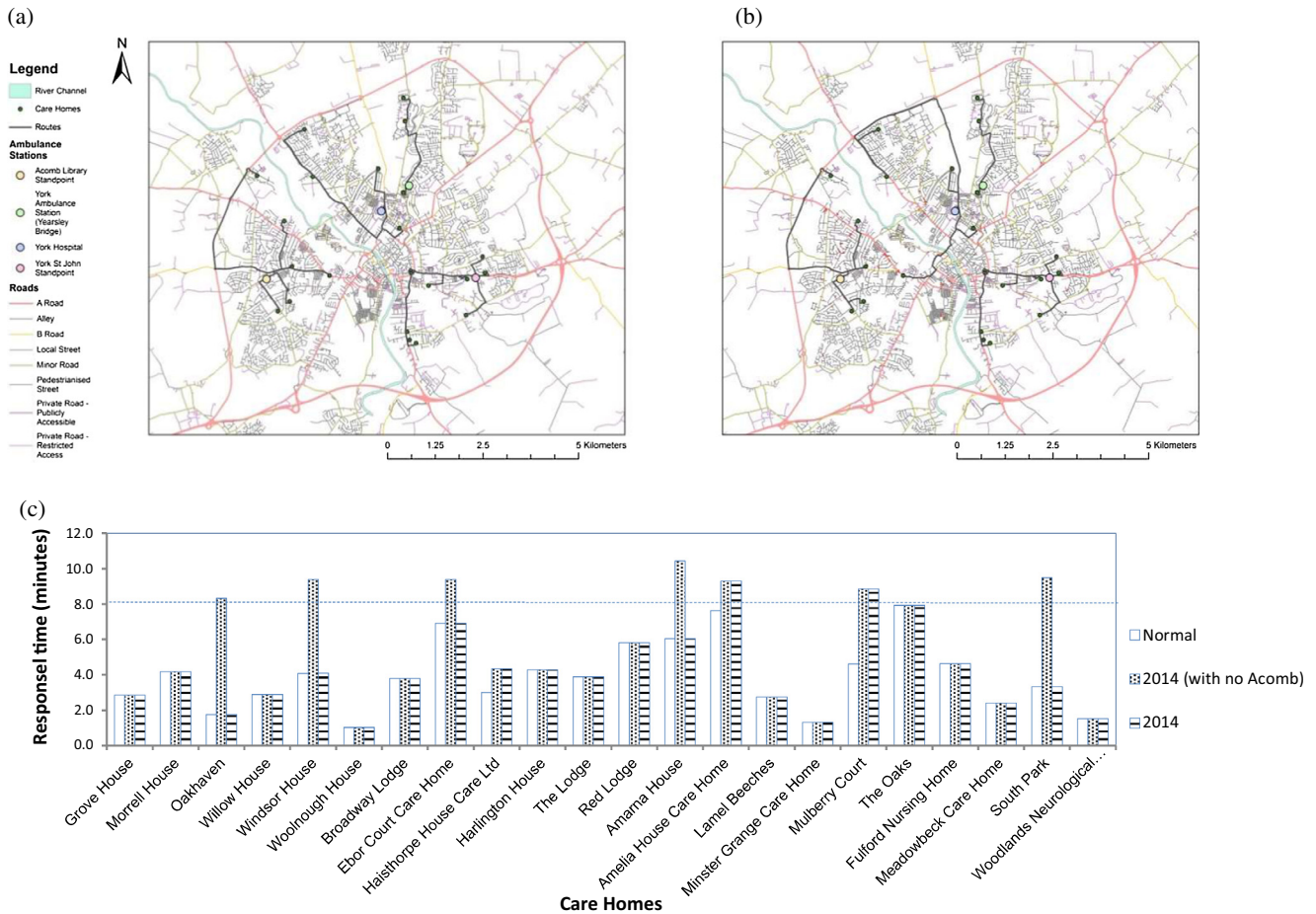


Fig. 12. Closest facility analysis for the Ambulance Service to care homes in York under (a) normal conditions, (b) for the modelled 2014 surface water flood event, and (c) a graph showing ambulance response times to care homes in York.

porating historical traffic data into the network modelling (Winn, 2014). Using historic traffic data, Cho and Yoon (2015) discovered that the performance of the emergency medical services was highly dependent on traffic conditions in the city of Seoul, South Korea. Sohn (2006) found that, for Maryland in USA, the significance of road links which are disrupted due to flooding depends upon whether traffic is considered along with distance. Koetse and Rietveld (2009) show that adverse weather conditions can cause traffic to slow down and also make road accidents more likely. Therefore, this is likely, with the addition of road closures, to further delay emergency response during periods of heavy rainfall and flooding.

Third, floods are dynamic, with changing water depth and velocity over time and space. Using either the modelled or observed maximum flood extent may not represent the accessibility at a particular time during the flood. This may not be a problem for the fluvial event simulated herein as fluvial events tend to generate maximum depth and extent for the whole area at the same time. For rapidly developing surface water flood events with complex spatial and temporal rainfall dynamics, maximum depths for different city regions are likely to occur at different time. Future studies could be undertaken to evaluate the spatial and temporal accessibility of a city during flood events.

The approach outlined in Fig. 1 also includes velocity as a criterion that can be used to define flood restrictions, in combination with water depth. This is particularly relevant for flash flooding when fast flowing water poses threats to life and assets. Future improvements could include developing a velocity threshold, in

conjunction with depth threshold to account for flooding with fast flood wave propagation.

In terms of fluvial flooding, current flood defences in York may give the public a false sense of protection as the design standard is for a 1 in 100-year event. However, recent flood events in the city during December 2015 highlighted that flood defences may not be sufficient under a changing climate. Prudhomme et al. (2012) find that a given flood magnitude in York calculated for the present may become much more frequent in the 2050 s and 2080 s. Emergency responders should plan for defences not performing to their current design standard and also for a future in which extensive flooding may become more frequent. Consequently, emergency services would need to adjust their operations in order to achieve the same legislated timeframes when operating during flood conditions. Such adjustments might include use of more real-time flood and traffic information to guide route selection when attending emergencies, design of vehicles that can pass safely through deeper waters, and more contingency planning for air or boat transport.

Accessibility analysis can also provide support to guide strategic and operational decision making of the emergency responders. For example, the Shropshire Fire and Rescue Service in the UK have outlined a plan for maintaining response times in Shrewsbury during a major flood event (Labouchardiere, 2007). Roads that would be impassable, with a flood depth in excess of 30 cm, are listed and suggestions are made for where to relocate fire appliances to maintain adequate service area coverage. This could be a useful strategy that other cities in the UK could adopt. Similar analysis

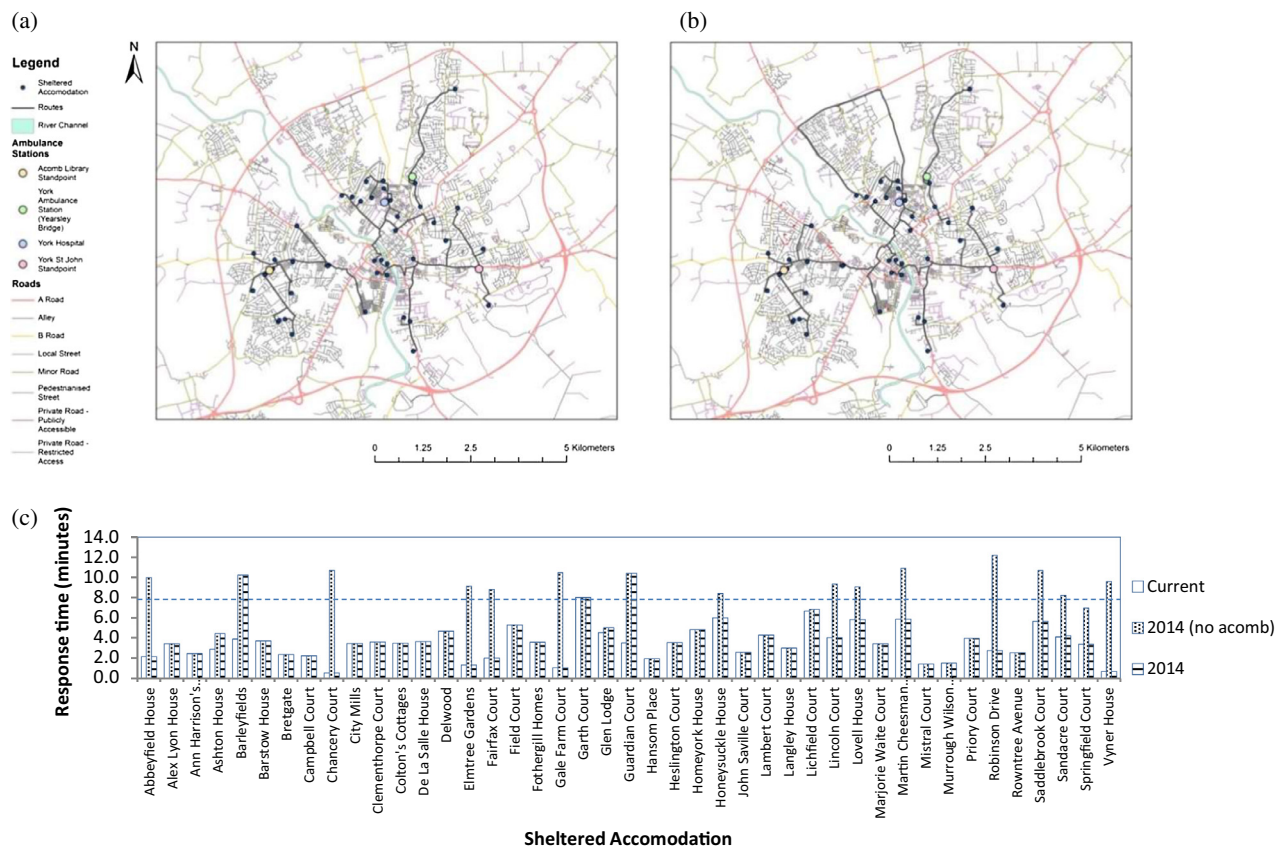


Fig. 13. As in Fig. 12 but for sheltered accommodation locations in York.

based on floods of various magnitude has been undertaken for Leicester by Green et al. (2017) using a scenario-based approach. In combination with evaluation of emergency accessibility based on historical events and potentially real-time forecasting of accessibility, strategic and operational decisions could be implemented accordingly. Establishing which parts of the transportation system are crucial to the operation of the network during flooding allows development of resilience strategies to maintain the operation of these linkages (e.g. Albano et al., 2014). For example, measures can be taken to alleviate potential disruptions to the system, such as allocating emergency pumping equipment to remove flood water (Sohn, 2006) or by positioning additional emergency vehicles in strategic locations ahead of a potentially disruptive flood.

Early warning systems and real-time flood forecasting may provide timely information for emergency responders for operational purposes. Versini (2012) found that predictions of road inundations up to 45 min prior to an event could provide emergency services with another source of information, along with visual evidence, to aid decision making. Moreover, surface water flood warnings, generated from Extreme Rainfall Alerts (ERAs), may be useful for emergency services in the UK to increase preparedness. Interviews conducted by Parker et al. (2011) suggest that 86% of professional emergency responders (PERs) would find alerts useful. Indeed, the Pitt Review (2008) recommended that real time mapping and visualisation of flooding should be available at every Gold Command. However, the lead-time and spatial resolution of many existing real-time mapping systems are often insufficient for emergency responses and lack real-time analysis of accessibility. Parker et al. (2011) found that increasing the reliability, spatial resolution and lead-time of the warnings would lead to greater percentage of PERs taking action on receiving ERAs.

Furthermore, although numerical simulation of flood inundation has advanced in recent years, there remain inherent uncertainties in the modelling. Uncertainty originates primarily from: (i) topographic representation; (ii) inflow boundary conditions (rainfall input and inflow uncertainty), and (iii) lack of observation data for model calibration and validation. The original LiDAR data has a vertical accuracy of ± 15 cm. However, spatial interpolation from LiDAR point clouds into a Digital Elevation Model will result in uncertainty in floodplain topography. Especially, when using a coarse mesh, structural features such as flood defences and blockage features on the urban landscape may not be represented adequately.

Other sources of uncertainty were encountered in this study. Flood defences had to be incorporated into the topography according to their heights by raising the pixels that overlap with the flood defences. The surface water flood modelling may incur uncertainty due to the dynamic nature of rainfall, especially over large domains. Similarly, inflow boundary condition specified at the upstream boundary condition can also have considerable uncertainties, especially for the peak flow measurement, due to instrument errors or peak flow bypassing gauging stations. Observational data are used for model validation and calibration, but they can also be inherently uncertain, especially in urban areas where high-rise buildings may obstruct a sensor's view due to its oblique angle. In addition, the all-weather InSAR technology (e.g. Sentinel-2) has limited application in observing urban flooding as smooth features such as road surface has similar spectral signature as water body. The flood extent of the 2015 fluvial event was obtained by the Environment Agency based on post-flood field survey which inevitably involves uncertainties. Surface water flooding observation often takes the form of discrete observation, rather than an overall assessment. In this study, reports from media

sources were used which cannot give a full understanding of the surface water flooding which occurred during the event. Uncertainties in the modelling process will translate into uncertainties in the accessibility mapping. Future modelling and accessibility studies could benefit from the improvement in the aforementioned fields.

5. Conclusion

This study integrates hydrodynamic modelling with geographical accessibility analysis to assess vulnerability of emergency services to fluvial and surface water flooding. The impact of two flood events was evaluated for the emergency services in the City of York. Changes to service area coverage and response times to vulnerable locations (care homes and sheltered accommodation) were quantified and mapped for the Ambulance and Fire & Rescue Services. The results highlight the vulnerability of the city in terms of emergency service access during flooding. An event in December 2015 had notable impacts on accessibility by emergency services within legislated timeframes, especially to the southeast of the city (River Foss) where extensive fluvial flooding occurred. Although it was a relatively localised surface water flood, the 2014 event caused widespread disruptions to a number of places in the city, especially on the west side.

The understanding gained through this analysis can be used by decision makers to design contingency plan for vulnerable populations. For example, the quantitative analysis shown in Figs. 11 and 12 enables decision makers to identify care homes that are most vulnerable to flooding impacts or prolonged response time by emergency services. Acknowledging this vulnerability is a first step towards development of contingency plans.

The quantitative impact on service areas and travel times during floods is clearly site-specific – different results would be expected in other cities depending on local topography, the natural and artificial drainage, configuration of the transport network, location of response nodes, and meteorological conditions generating the flood. In the case of York, the impacts of the events are manageable. However, the modelled response times are likely underestimated as we assumed normal traffic, excluded dispatch time and did not consider the interaction between adverse weather and traffic disruption. Under a changing climate where we expect more frequent and intense precipitation, emergency responders may need to consider other options and innovative contingency measures to meet the legislative targets for emergency cover under flood conditions. Vulnerable sites (such as care homes) that are still beyond the reach of emergency services might review their own flood plans in the light of this information.

Looking beyond flood hot spots where flood risks are immediate, this study demonstrated an approach to investigating the wider cascading impacts of road blockages on emergency service provision, highlighting the interdependence between infrastructure networks and vulnerability (HMG, 2016). The approach described in this study allows emergency responders to evaluate the resilience of their services during flooding. Understanding can be gained through simulation analysis based on historical and scenario-based events to identify vulnerability and provide support for strategic planning. The readily transferrable approach also opens up research opportunities for exploring the impacts of traffic and demographic changes on emergency services in a changing climate and urban environment.

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